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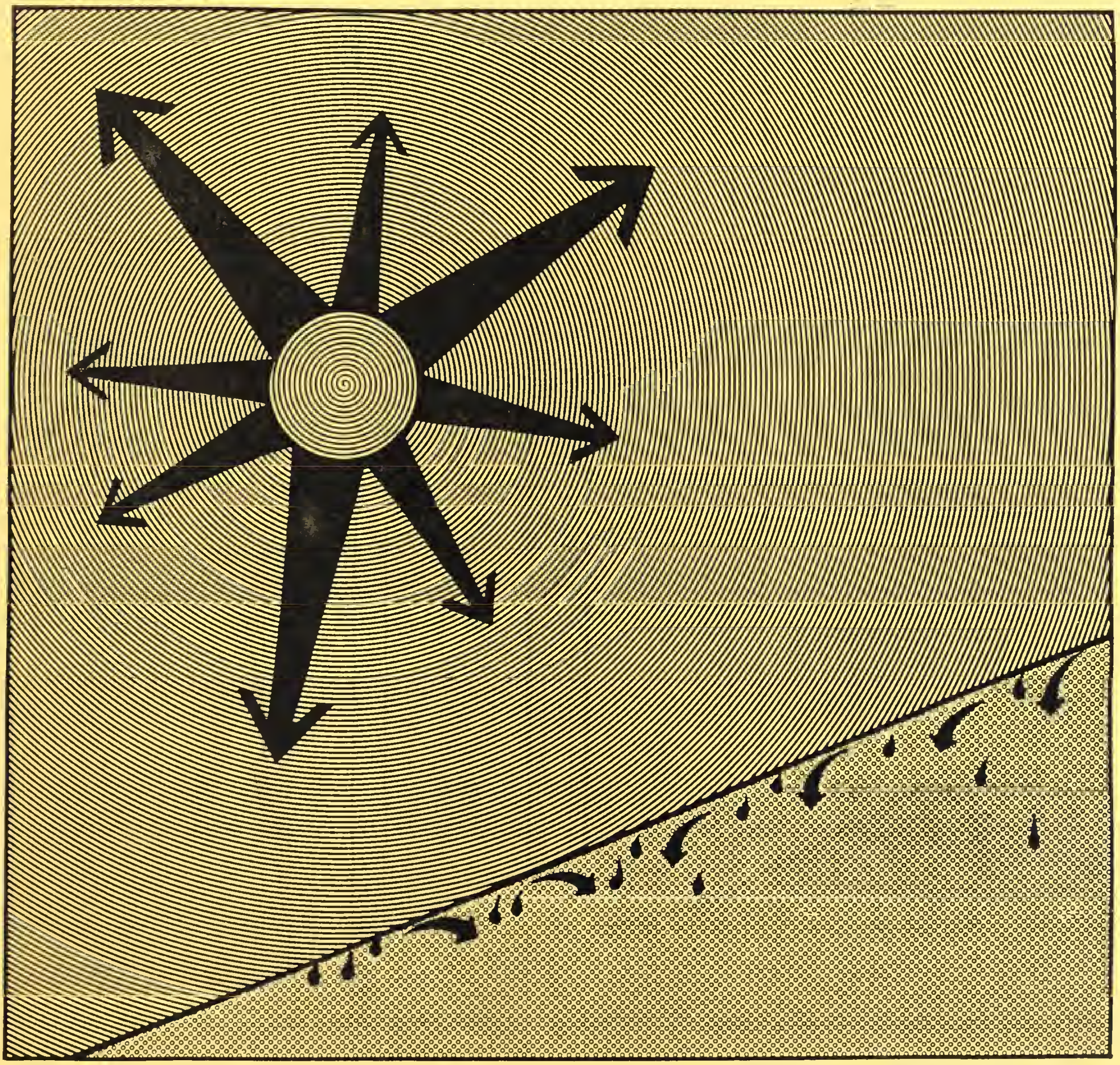
Forestry
Management

Forest Service
Denver, Colorado

SOIL SOLAR HEATING

at the Bessey Nursery, Halsey, Nebraska



SOIL SOLAR HEATING FOR REDUCTION IN POPULATIONS OF *PYTHIUM*, *FUSARIUM*, NEMATODES, AND WEEDS AT THE U.S. FOREST SERVICE BESSEY TREE NURSERY, HALSEY, NEBRASKA

BY

DIANE M. HILDEBRAND
PLANT PATHOLOGIST

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TIMBER, FOREST PEST, AND COOPERATIVE FORESTRY MANAGEMENT
ROCKY MOUNTAIN REGION
USDA FOREST SERVICE
11177 W. 8TH AVENUE
LAKEWOOD, COLORADO 80225

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ABSTRACT

At the Bessey Nursery, Halsey, Nebraska, three plots (3 x 15 m) were covered with 0.02 mm clear polyethylene tarp for solar heating for eight weeks (June 21 to August 17) in summer 1983, and three plots were left fallow as checks. In spring 1984, three plots were fumigated with methyl bromide/chloropicrin prior to planting all plots with lodgepole pine seed. Soil samples were taken before and after soil treatments. Populations of *Pythium* spp. were significantly reduced by solar heating, but returned to high levels by spring, probably due to the effects of the sudangrass winter cover crop. Fumigation was less effective than solar heating in reducing populations of *Pythium* spp. in samples taken immediately after treatment. Reductions in populations of *Fusarium* spp. by solar heating were not statistically significant, and in samples taken immediately after treatment, reductions due to fumigation were similar to those due to solar heating. Population levels of plant-parasitic nematodes were low throughout the study, and reductions were due to solar heating combined with the bare-ground conditions. In samples taken immediately after treatment, fumigation was less effective than solar heating in reducing nematode populations; fumigated plots were under cover crop the entire summer and winter before fumigation. Weed populations were significantly reduced by solar heating, but returned to pre-treatment levels by the following spring. In samples taken immediately after treatment, solar heating was as effective as fumigation for weed control. No significant effects on lodgepole pine seedling survival resulted from any of the treatments. The winter cover crop grew more lush and darker green in solar plot locations than in the surrounding check area. Seasonal effects on soil chemistry were greater than solar heating effects.

INTRODUCTION

Weeds and plant pathogens such as nematodes and soil-borne fungi often cause significant seedling losses in forest tree nurseries. Chemical fumigation of the soil is the best control method at present because fungal pathogens and weeds are greatly reduced in a single application (Gillman, 1977). Although soil fumigation in forest nurseries is cost effective (Landis et al., 1976), populations of desirable microrganisms such as mycorrhizal fungi are significantly reduced (Munnecke and Van Gundy, 1979). In addition, fumigation chemicals are hazardous, requiring special handling and disposal procedures.

A less expensive and less hazardous method for control of soil-borne pests is solar heating. Solar heating of soil (also referred to as solarization or solar pasteurization) is a recently developed technique in which moist soil is covered with clear polyethylene tarp for several weeks during the hottest part of the growing season for control of soil-borne pathogens and weeds (Katan et al., 1976).

In some locations, the polyethylene tarp allows solar radiation to increase soil temperatures to over $40^{\circ}C$ at 30 cm depth (Pullman et al., 1981b), chiefly by eliminating evaporation and partly by the greenhouse effect (Mahrer, 1979). Continuous or repeated sub-lethal temperatures under moist conditions over long periods either kill pathogenic fungi directly or weaken them so they cannot compete effectively with saprophytes. In laboratory tests, 90% of the propagules of *Verticillium dahliae* Kleb. died after 2 hours at $45^{\circ}C$ or after 7 days at $38.5^{\circ}C$ in natural field soil, while in pure culture at $45^{\circ}C$, 7 hours were required for 90% mortality (Pullman et al., 1981a). Apparently, plant pathogens are more sensitive to elevated temperatures than are saprophytes. Mycorrhizal fungi such as *Glomus fasciculatus* (Thaxter) Gerd. & Trappe can survive solar heating and colonize crop roots (Pullman et al., 1981b). Solar heating of soil alters the balance of microorganisms to the detriment of plant pathogens, and thus solar pasteurization can be considered an integrated pest management technique (Katan, 1980). Solar heating has been effective against a variety of weeds and soil-borne pathogens, especially for agricultural crops in Israel and California. (Grinstein et al., 1979; Solarization Research Team, 1981, Jacobsohn et al., 1980; Horowitz et al., 1983, Pullman et al., 1981b; Ashworth and Gaona, 1982). Studies also showed that disease reduction was still evident the second growing season after solar heating (Katan et al., 1981; Pullman et al., 1981b).

Solar heating may affect soil chemistry. For example, increases in nitrate and ammonium nitrogen, potassium, calcium, magnesium, chloride, and phosphate in the soil solution have been reported (Stapleton et al., 1983; Chen and Katan, 1980). Disease reduction and increase in soluble minerals may contribute to the increased growth response observed in crops grown in solar heated soil.

Solar heating of soil in conifer nurseries has been evaluated recently in a few areas of the United States. Results at the Iowa State Nursery, Ames, (Croghan et al., 1984) indicated reductions in populations of weeds and saprophytic nematodes from solar heating, but no significant decreases in populations of *Fusarium* spp. In trials at the Bend Nursery in eastern Oregon, Cooley (1983) found that populations of *Fusarium* spp. were significantly reduced by solar heating, but tree seedling survival after 10 weeks was similar in check and solar heated plots. Results at the J. Herbert Stone Nursery, Medford, Oregon (Cooley, 1985) indicated significant reductions in populations of *Fusarium* spp.

due to solar heating, but again seedling survival was not improved. Zarnstorff (1983) in Wisconsin found no significant reductions in populations of *F. oxysporum* *Schlect.*, *Rhizoctonia solani* Kuehn, or *Cylindrocladium floridanum* Sobers & Seymour after solar heating. McCain, *et al.*, (1982) found that *F. oxysporum* was eliminated in soil to 10 cm depth and reduced in soil between 10 and 20 cm, while *Macrophomina phaseolina* (Tassi) Gold, survived at all depths after solar heating in a northern California nursery near Placerville. At the Colorado State Forest Service Nursery, Fort Collins, solar heating resulted in significant reductions in population of weeds and species of *Fusarium* and *Pythium* (Hildebrand, 1984).

This evaluation was undertaken (1) to assess the effectiveness of solar heating in reducing population levels of plant-parasitic nematodes, weeds, and species of *Pythium* and *Fusarium*, (2) to determine whether solar heating affects soil chemistry, and (3) to compare lodgepole pine seedling survival in check, solar heated, and fumigated plots at the U. S. Forest Service Bessey Tree Nursery, Nebraska.

MATERIALS AND METHODS

The Bessey Nursery is located 3 km west of Halsey, Thomas County, Nebraska at 838 m elevation. The soil in the study area is Meadin loamy sand of the Dunday Loup Association in the Middle Loup River Valley (Sherfey *et al.*, 1965). The Bessey Nursery has had a history of damping-off (Hunt, 1965) and nematode damage (Peterson, 1962).

Soil Treatments

In summer 1983, six treatment plots (3.2 m x 15.2 m) were arranged in a randomized block design parallel with nursery beds. After irrigation to field capacity, three plots were covered with 0.02 mm (1 1/2 mil) thick clear polyethylene tarp for eight weeks for solar heating, and three plots were left fallow as checks (Figures 1-3). Before tarp placement, six Peabody/Ryan model J thermographs were buried to monitor range and duration of temperatures. One thermograph was buried at 8 cm, one at 15 cm, and one at 30 cm, several feet apart, near the center of one check and one solar plot. Check plots were periodically lightly cultivated to prevent weed cover during the summer 1983. A cover crop of Piper sudangrass was planted in all plots over the 83-84 winter (Figure 4). In late April 1984, the cover crop was plowed under and fumigation with methyl bromide/chloropicrin accomplished in 3 additional plots which had been under cover crop continuously since June 1983.

Soil Assays for Fungi, Nematodes, and Weeds

Soil was assayed for populations of species of *Pythium*, *Fusarium*, and nematodes. Each sample was a composite of ten 15 cm soil probe cores. Four samples were taken in each treatment plot. Additional deeper samples for nematodes were collected with a soil bucket auger, with one bucketful (approximately 1 liter) per sample and four samples per treatment plot.

Assay for species of *Pythium* and *Fusarium* were similar to procedures used by Johnson and Zak (1977), except 3 plates of selective medium were used per sample. Soil samples for nematode counts were processed using a wet-sieving, centrifugation-sucrose-flotation technique (Goodey, 1963, modified by Riffle, 1983).

PLATE I

Figure 1. Roller attachment used to simultaneously lay tarp and bury the edges with soil at the Bessey Nursery.

Figure 2. Three plots (foreground) covered with polyethylene tarp for solar heating at the Bessey Nursery.

Figure 3. Tractor with roller laying tarp at the Bessey Nursery.

Figure 4. Piper sudangrass cover crop in study area in November 1984. Dark green lush growth coincides with locations of solar-heated plots.

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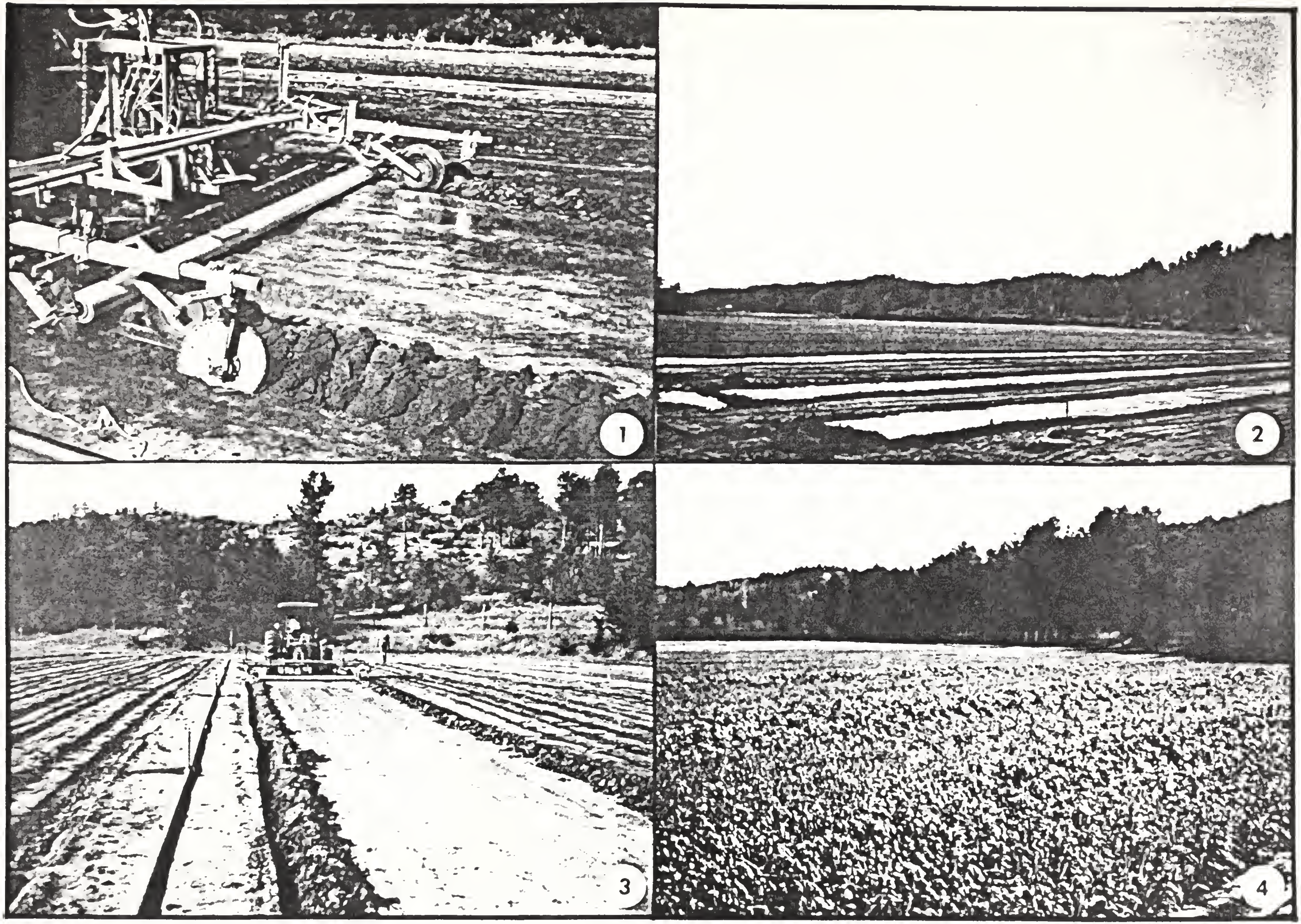
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Soil for weed-seed germination tests was collected from the surface to a depth of 2.5 cm from within a 929 cm^2 frame for each sample, with four samples taken per treatment plot. Each weed soil sample was poured into a foil pan, watered, and kept in a Scherer Environmental Chamber with 12 hours light at 25°C and 12 hours dark at 18°C. After two weeks, weed seedlings were counted.

Soil Chemical Analyses

Samples for soil chemical analyses were composites of nine probe cores taken 6 m from the ends of one solar and one check plot. The two sample locations were less than 4.6 m apart, on either side of an irrigation line. Samples for soil chemical properties were processed by the Colorado State University (CSU) Soils Testing Lab. Analyses included particle size distribution, bulk density, organic matter, and the following from a 1:1 soil and water extract: pH, electrical conductivity, and ions of calcium, magnesium, potassium, sodium, nitrate, ammonium, and chloride.

A complete series of the above soil samples for pest assays and for chemical analyses were taken before tarp placement in June 1983, after tarp removal in August 1983, and the following spring, 1984. Samples were taken from nearly identical locations for each of the sampling times. The spring 1984 samples were taken at the end of May and an additional set for fungi and nematode assays were taken in June 1984 when lodgepole pine seedlings were about 4 weeks old.

Tree Seedling Survival

A crop of lodgepole pine was sown in May 1984 to evaluate solar heating treatment effects on seedling survival. Five subplots (30 cm along the bed x 76 cm across the bed, encompassing 4 rows) were monitored in each of the nine treatment plots (3 check, 3 solar, 3 fumigated). The number of surviving seedlings were counted beginning May 25, 1984 (two weeks after sowing) and then approximately every 2 weeks through July 17. A final count was made on October 1, 1984.

Data Analyses

Significant differences in treatment effects between solar heated, fumigated, and check plot populations of species of *Pythium*, *Fusarium*, plant-parasitic nematodes and weeds were determined by two-way analysis of variance when homoscedasticity could be achieved by data transformation. Otherwise, the "test for equality of means whose variance are assumed to be unequal" (Sokal and Rohlf, 1981) was used. Significant differences in tree seedling survival between treatments were determined by single classification analysis of variance.

RESULTS

Soil Temperature

Figure 5 summarizes the weekly averages of the daily high temperatures recorded by the six thermographs with their sensors buried at 8, 15, and 30 cm in each of one check and one solar plot. Temperatures overall averaged 6.5°C higher in solar-heated than in check plots, while highest temperatures averaged 8°C higher in solar than in check plots. The temperature record at 8 cm for the last two weeks in the solar plot was lost. Table A1 in the appendix presents weekly average high temperatures and their durations recorded by the six thermographs.

Pythium spp.

Table 1 presents means, variances and the results of the test of equality of means for populations of *Pythium* spp. in check, solar, and fumigated plots. Initially, the population levels of *Pythium* spp. were different between check and solar plots before tarp application in June '83. By August '83, the solar heating treatment significantly reduced population levels in solar plots while those in check plots remained similar to June '83 levels. By the following spring, population levels of *Pythium* spp. had returned to or exceeded pretreatment levels. The solar heating treatment was more effective than fumigation when comparing samples taken immediately after treatment.

Table 1. Means, variances, and results of the test for equality of means for population levels of *Pythium* spp. in propagules per gram of oven-dried soil.

Date	Treatment	Variance	Mean *
June 1983	Check	1891.85	42.2 cde
	Solar	68.05	7.3 b
August 1983	Check	285.96	30.4 cd
	Solar	0.14	0.3 a
May 1984	Check	681.90	49.9 de
	Solar	599.79	54.8 e
	Fumigated	99.70	11.4 b
June 1984	Check	1424.57	43.1 cde
	Solar	677.07	59.1 e
	Fumigated	362.85	26.8 c

* Means followed by the same letter are not significantly different at $P<0.05$.

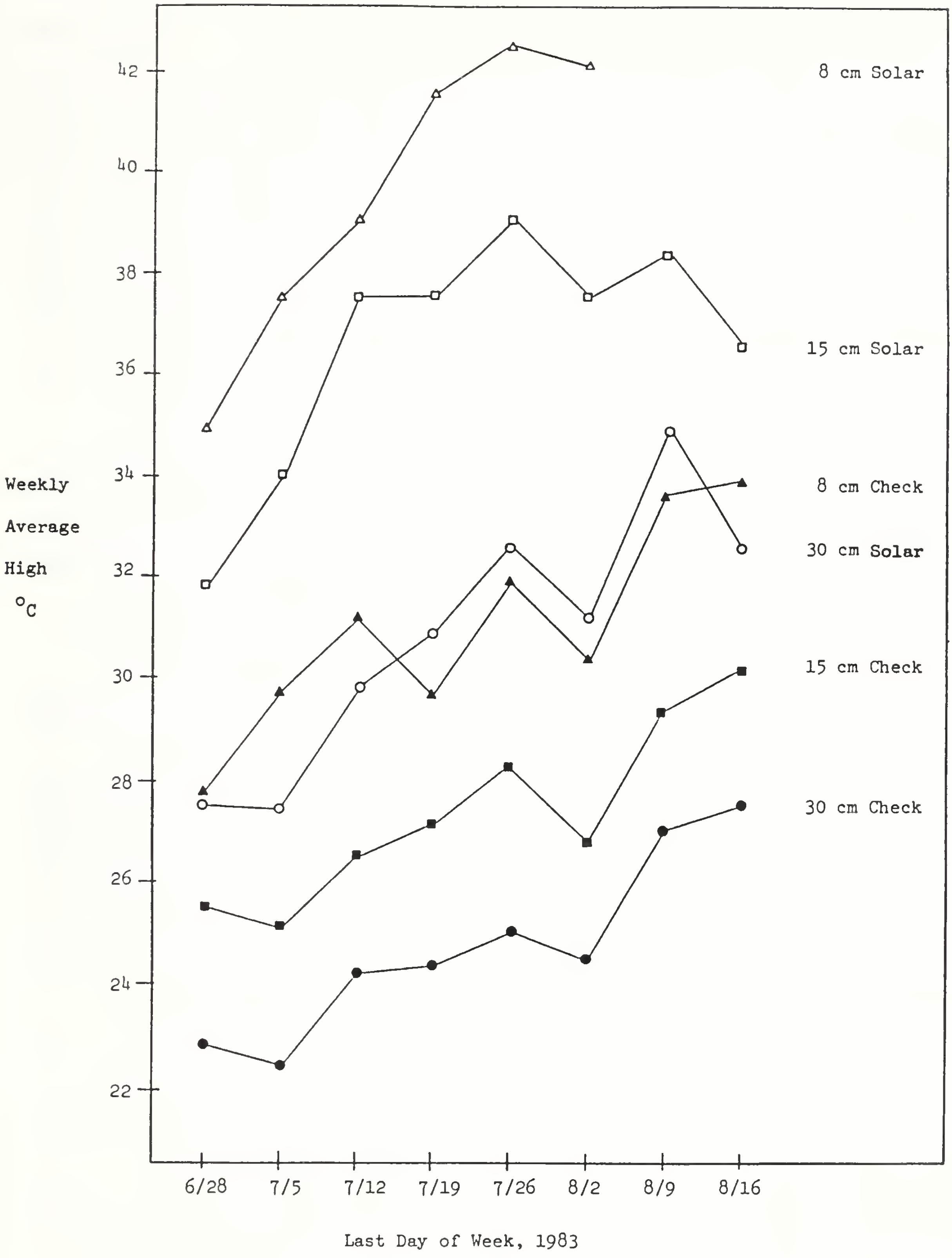

Figure 5. Weekly average high temperatures recorded by thermographs buried at 8, 15, and 30 cm in each of one check and one solar-heated plot.

Fusarium spp.

Results of two-way analyses of variance for population levels of *Fusarium* spp. are shown in Table 2. In the analysis, population levels (as propagules per gram of air-dried soil transformed by $Y' = \sqrt{Y + 3/8}$) are compared for check and solar treatments in June (before treatment) and August 1983 (after treatment). This analysis should show the strongest solar heating effect. If the solar heating treatment effect were significant, population changes over time in the solar plots would differ from population changes over time in the check plots, resulting in a significant interaction (Green, 1979). The analysis, however, only shows that the populations of *Fusarium* spp. in the solar plots were consistently different from (less than) those in check plots. No effect of solar heating is shown statistically.

Table 2. Two-way table with sub-group means and results of two-way analysis of variance for population levels of *Fusarium* spp. in check and solar treatment plots in June and August 1983.

Means*			Source of Variation	df	MS	F
	Date					
Treatment	June 1983	August 1983	Treatment	1	1593.49	24.94***
			Date	1	125.18	1.96 ns
Check	20.1	19.8	Interaction	1	97.78	1.56 ns
Solar	11.5	5.4	Within subgroups	44	63.87	

*Propagules per gram of soil transformed by $Y' = \sqrt{Y + 3/8}$
*** significant at $P<0.001$; ns = not significant

Table 3 presents means of population levels of *Fusarium* spp. in check, solar-heated, and fumigated plots for the June and August 1983, and May and June 1984 sampling times. Results of two-way analyses of variance for population levels of *Fusarium* spp. in check and solar treatment plots in August 1983 and May 1984 and in May and June 1984 are given in Tables A2 and A3 in the Appendix. Population levels of *Fusarium* spp. dropped considerably over the winter in check plots, while remaining at relatively unchanged lower levels in the solar plots. By May 1984, population levels of *Fusarium* spp. were similar in check and solar plots, and population levels increased by June 1984.

Table 3. Means* of population levels of *Fusarium* spp. in check, solar-heated and fumigated plots in June and August 1983, and May and June 1984.

Treatment	June 1983	August 1983	May 1984	June 1984
Check	20.1	19.8	10.0	16.2
Solar	11.5	5.4	6.4	10.2
Fumigated	-	-	2.6	6.4

* Propagules per gram of soil transformed by $Y = \sqrt{Y + 3/8}$

Table A4 in the Appendix presents results of a single classification analysis of variance for population levels of *Fusarium* spp. in June 1984, in check, solar-heated, and fumigated plots. The analysis indicates a significant difference between the three treatments. Orthogonal comparisons showed that check and solar treatments were similar, and solar and fumigated treatments

were similar in the June 1984 samples. The test for equality of means showed no significant difference between population levels of *Fusarium* spp. in solar-heated and fumigated plots in May 1984. Fumigation was similar in effectiveness to solar-heating in reducing populations of *Fusarium* spp.

Plant-parasitic Nematodes

Populations of plant-parasitic nematodes were estimated by counting the number extracted from 250 ml field moist soil. Genera encountered included, in order of abundance: *Trichodorus*, *Tylenchus*, *Tylenchorynchus*, *Helicotylenchus*, *Xiphinema*, and *Pratylenchus*. The number of individuals of *Trichodorus* sp. was greater than that in all other genera combined. The population levels of the other plant-parasitic nematode genera were quite low (<2 worms per genus in 250 ml soil) throughout the study area.

Population levels of plant-parasitic nematode genera were compared using the test for equality of means whose variances are unequal. Table 6 shows the significant differences (P<0.05) in means for populations of plant-parastic nematodes in check and solar plots in June 1983 (before treatment) and in August 1983 (after treatment) for 4 different depths: A = 0-15 cm, B = 15-30 cm, C = 30-42 cm, and D = 43-56 cm.

Table 6. Variances and means of populations of plant-parasitic nematodes per 250 ml soil in June and August 1983 in check and solar heated plots at four depths.

Treatment	June 1983			August 1983	
	Sample Depth*	Variance	Mean **	Variance	Mean**
Check	A	42.42	10.3 de	8.99	3.1 abc
	B	67.90	4.4 abcd	20.99	2.1 abc
	C	58.15	3.8 abc	18.42	1.7 abc
	D	22.63	2.9 abc	5.17	1.6 ab
Solar	A	120.57	17.8 e	0.08	0.1 a
	B	28.93	5.3 bcd	0.08	0.1 a
	C	39.36	5.9 cd	4.08	0.6 a
	D	110.08	5.9 abcd	5.42	1.2 a

* Soil sample depth: A = 0-15 cm, B = 15-30 cm, C = 30-43 cm, D = 43-56 cm.
** Means followed by the same letter are not significantly different at P<0.05

In check plots, population levels of plant-parasitic nematodes declined significantly between June and August 1983, but only in the A (0-15 cm) depth samples. In solar plots, population levels of plant-parasitic nematodes dropped significantly to a depth of 43 cm. Because of the overall low population levels, high variability, and irregular distribution, there are no adequate statistical tests for these data, and no significant differences were shown statistically between check and solar heated plots in August 1983.

Table 7 presents means for populations of plant-parasitic nematodes in May and July, 1984, in check, solar, and fumigated plots at A = 0-15 cm and B = 15-30 cm depths. Fumigated plots had been covered with sudangrass the entire summer and winter from June 1983 through April 1984. Essentially all of the nematodes encountered in 1984 were *Trichodorus* sp. Other than in the May fumigated samples, population levels of plant-parasitic nematodes were very low and not significantly different in all other plots in spring and summer 1984, after planting with lodgepole pine.

Table 7. Variances and means of populations of plant-parasitic nematodes per 250 ml soil in May and July 1984 in check, solar, and fumigated plots at A = 0-15 cm and B = 15-30 cm depths.

Treatment	Sample Depth	May 1984		July 1984	
		Variance	Mean*	Variance	Mean
Check	A	0.64	0.1 a	0.15	0.2 a
	B	0	0 a	0.15	0.2 a
Solar	A	4.75	1.3 ab	0	0 a
	B	0.15	0.2 a	2.08	0.6 a
Fumigated	A	17.17	3.4 b	0	0 a
	B	1869.17	32.9 c	0.39	0.3 a

* Means followed by the same letter are not significantly different at P<0.05.

Weeds

A variety of weeds occurred in the treatment area including volunteer sudangrass and chokecherry (*Prunus virginiana* L.) from a previous crop. The weeds included clover (*Trifolium* sp.), carpetweed (*Mollugo verticillata* L.), shepherd's purse (*Capsella bursa-pastoris* L.), downy brome (*Bromus tectorum* L.) and *Medicago* spp.

Weed populations were compared using the test for equality of means whose variances are unequal. Table 8 shows differences between weed populations (number per 929 cm^2) for June 1983, August 1983, and May 1984 check and solar samples, and May 1984 fumigated samples. By August 1983, solar heating was more effective in weed control than the periodic light cultivation performed in the check plots. By May 1984, weeds had returned to pretreatment levels in check and solar plots. In samples taken soon after treatment, solar heating was as effective as fumigation for weed control in the upper 2.5 cm of soil.

Table 8. Variances and means for weed populations (number per 929 cm^2) in check and solar plots in June 1983, August 1983, and May 1984, and in fumigated plots in May 1984.

Date	Treatment	Variance	Mean*
June 1983	Check	95.09	5.0 b
	Solar	0.45	0.4 b
August 1983	Check	139.90	9.9 c
	Solar	0	0 a
May 1984	Check	60.57	4.3 b
	Solar	0.24	0.3 b
	Fumigated	0	0 a

* Means followed by the same letter are not significantly different at P<0.05.

Soil Chemical Analysis

Tables 9 and 10 present the results of the soil chemical analyses for samples taken from one check and one solar plot. If one looked only at the differences between the check and solar plot results for August (after treatment), increases would be evident in calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), chloride (Cl), ammonium nitrogen (NH_4-N), nitrate nitrogen (NO_3-N), pH, electrical conductivity, and silt. Decreases would be evident in bulk density, organic matter, soil and clay. However, considering the June pretreatment values, seasonal effects were greater than any apparent solar heating effects, except perhaps for Ca and NH_4-N.

Table 9. Results of soil chemical analyses for samples taken in one solar and one check plot in June (J), before treatment, August (A) after tarps were removed, and the following May (M). Ions, pH and electrical conductivity were measured in soil extract (1:1 soil to water for sandy soil).

Sample	Ca mg/ℓ			Mg mg/ℓ			Na mg/ℓ			K mg/ℓ			Cl mg/ℓ		
	J	A	M	J	A	M	J	A	M	J	A	M	J	A	M
Check	7.7	12	51	1.8	3	12	2.0	3	-	5.4	8	6	6	4	6
Solar	8.6	26	47	2.4	4	11	2.4	5	-	7.3	11	6	5	5	4

Sample	NH_4-N mg/ℓ			NO_3-N mg/ ℓ			pH			Electrical Conductivity x10^3			Total Organic Matter		
	J	A	M	J	A	M	J	A	M	J	A	M	J	A	M
Check	0.4	0.6	6	1.9	7	8	5.7	5.3	5.5	0.1	0.1	0.5	1.4	1.0	1.0
Solar	0.7	2.4	3	3.5	12	6	5.7	5.8	5.2	0.1	0.2	0.4	1.4	1.0	1.0

Table 10. Results of soil physical analyses for samples taken in one solar and one check plot in June (J), before treatment, August (A) after tarps were removed, and the following May (M).

Sample	% Sand			% Silt			% Clay			Texture			Bulk Density g/cm^3		
	J	A	M	J	A	M	J	A	M	J	A	M	J	A	M
Check	86	88	86	11	9	9	3	3	5	LS	S	LS	1.55	1.69	1.6
Solar	86	86	86	10	12	8	4	2	6	LS	LS/S	LS	1.63	1.46	1.6

Tree Seedling Survival

Over all plots and treatments, most of the lodgepole pine mortality occurred at the beginning of the growing season. Seedlings continued to die at a slow rate through October 1984. On the average, fumigated plots yielded 21.3 seedlings/ft^2 (929 cm^2), check plots 14.3 seedling/ft^2, and solar heated plots 12.4 seedlings/ft^2. Due to the high variability within treatments, analysis of variance indicated no significant effects on seedling survival between any of the treatments. Table 11 presents means and results of analysis of variance for check, solar, and fumigated treatments for lodgepole pine seedlings in October 1984. Table A5 in the Appendix presents the average number of surviving seedlings per ft^2 by plot at 3 counting times. By October 1, 1984, losses in solar-heated plots were 31%, in check plots 27%, and in fumigated plots 17% of the number of live seedlings on May 25.

Table 11. Means and results of analysis of variance for the surviving lodgepole pine seedlings in check, solar heated, and fumigated plots in October 1984.

Treatment	Means*	Source of Variation	df	MS	F
Check	14.3	Treatment Effects	2	65.57	2.84 ns
Solar	12.4	Within Groups	6	23.07	
Fumigated	21.3				

*seedlings per square foot (929 cm^2)
ns = not significant

DISCUSSION AND SUMMARY

Populations of Soilborne Pests

Populations of *Pythium* spp. were significantly reduced by the solar heating treatment, but levels returned to pretreatment levels by the following spring,probably due to the effects of the sudangrass cover crop. Fumigation was less effective than solar heating in controlling *Pythium* spp. in samples taken immediately after treatment. Reductions in populations of *Fusarium* spp. due to solar heating were not statistically significant, and reductions due to fumigation were similar to those due to solar heating.

Population levels of plant-parasitic nematode genera were fairly low throughout the study, and reductions due to solar heating were combined with reductions due to the bareground conditions. Fumigation was less effective than solar heating in controlling nematodes, but fumigated plots were under cover crop much longer than were the check and solar plots. The continuous vegetation cover may account for the higher levels of plant-parasitic nematode genera even immediately after fumigation. *Trichodorus* sp. apparently thrived on the sudangrass, but not on the lodgepole pine, because the high levels of *Trichodorus* in the fumigated plots in May 1984 declined sharply by July 1984. A probable reason for the mediocre results of fumigation was too little time between the plowing under of the cover crop and fumigation. A two to three week fallow period between cover crop plowing under and soil treatment would maximize the effectiveness of any soil treatment for pest reduction.

Population levels of weeds in the upper 2.5 cm of soil were significantly reduced by solar heating, but populations returned to pretreatment levels by the following spring. In samples taken immediately after treatment, solar heating was as effective as fumigation for weed control.

Soil Chemistry

Although the Soils Testing Lab was given the same instructions each time the pair of soil samples (from the one solar and one check plot) was submitted, considerable variation in results were obtained as illustrated in Tables 9 and 10. Although some variation in ions could be expected, particle size distribution should remain constant. The fluctuating values for particle size distribution indicate that any real differences due to solar heating could be obscured by the variation in results. It is doubtful that solar heating affected the chemistry of the soil solution. Seasonal effects were greater than any apparent solar heating effects except perhaps for calcium and NH_4-nitrogen. However, all changes may be artifacts due to the variability in the lab results.

These results underscore the danger of taking only post-treatment samples. Because a statistical sample is not taken for soil chemical analysis, more than one set of samples (e.g. pre-treatment and post-treatment for both check and treatment) should be taken. Seasonal variation may exceed any apparent change due to treatment, or the soil in the sampling areas may have differed before treatment.

Growth Response

Lodgepole pine seedlings planted in the study area the following spring showed no beneficial effects due to solar heating. The winter cover crop, however, was darker green and more lush in the solar heated plots compared with that in the surrounding check area (Figure 4), in November 1983. Some benefit in growth response may have been wasted on the cover crop.

Solar Heating in Practice

Both fumigation and solar heating require the use of tractor, personnel, tarps, and rollers; however, with solar heating the safety hazards and cost of handling the toxic fumigant are eliminated. The cost-savings on the price of the fumigant is conservatively estimated at $350 per acre (Hinz, 1984). A disadvantage of solar heating is that the area being treated must be out of production for 6 to 8 weeks during the summer preceeding planting. Fall-planted crops would benefit the most from the control of weeds, nematodes, and some soil fungi by solar heating. Even partial reduction in the annual cost of labor and herbicides for weeding ($340 per acre in addition to fumigation, Dinkel, 1985), makes the solar heating technique attractive. Solar heating effects on seedling survival in a fall-planted crop should be investigated in the Rocky Mountain Region.

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APPENDIX

Soil Temperature

Table A1 presents the weekly averages of the daily high temperatures and the duration in hours that the temperature was within 1°C of the daily high recorded by the six thermographs buried at 8, 15, and 30 cm depths in one check and one solar plot. The temperature achieved at 8 cm in the solar plot exceeded 46°C (the limit of the thermograph's recording capability) several times. At these times, the temperature remained above 45°C for two to six hours duration. The average duration at this temperature was 4.1 hours. While the temperature was off-scale (46+°C) on 8/2/83, the chart tore and the subsequent record was lost.

Analyses of Variance for Population Levels of FUSARIUM spp.

Results of two-way analyses of variance for population levels of *Fusarium* spp. are presented in Tables A2 and A3. In each analysis, population levels (as propagules per gram of air-dried soil transformed by $Y' = \sqrt{Y + 3/8}$) are compared as check and solar treatments by early and later sampling dates.

In Table A2, the early date is August 1983 (immediately after treatment) while the later date is May 1984 (the spring after treatment). The analysis shows a significant interaction between effects of treatment and date because population levels of *Fusarium* spp. dropped considerably over the winter in check plots, while remaining at relatively unchanged lower levels in the solar plots.

Table A1. Highest temperature achieved, weekly averages of daily high temperatures, and the duration in hours that the temperature was within 1°C of the daily high recorded by thermographs buried at 8, 15, and 30 cm depths in one check and one solar plot at Bessey Nursery, 1983.

Last Day of Week 1983	Thermograph and Highest Temp. (°C)	Ave. Daily High (°C)	Ave. Duration (Hours) at High Temp.	Thermograph and Highest Temp. (°C)	Ave. Daily High (°C)	Ave. Duration (Hours) at High Temp.
6/28		35.0	3.6		27.9	6.0
7/5	Solar 8cm	37.6	3.2	Check 8cm	29.7	3.8
7/12	46 +	39.1	3.1	36	31.2	3.5
7/19		41.5	2.9		29.7	5.1
7/26		42.5	4.0		31.9	3.6
8/2		42.1	2.9		30.4	4.1
8/9		-	-		33.5	3.6
8/16		-	-		33.8	3.3
6/28		31.8	4.4		25.5	5.4
7/5	Solar 15cm	34.1	4.4	Check 15cm	25.2	5.5
7/12	44	37.6	4.4	32.4	26.5	6.4
7/19		37.7	5.1		27.2	6.1
7/26		39.0	4.5		28.3	5.6
8/2		37.6	4.3		26.9	6.6
8/9		38.3	4.8		29.2	7.4
8/16		36.6	4.8		30.1	7.2
6/28		27.5	9.2		22.7	9.3
7/5	Solar 30cm	27.3	10.7	Check 30cm	22.4	7.8
7/12	35.9	29.8	10.5	28.0	24.2	7.8
7/19		30.9	11.1		24.3	7.6
7/26		32.5	8.7		25.1	11.8
8/2		31.2	10.8		24.4	12.0
8/9		34.8	8.7		27.0	11.9
8/16		32.5	10.6		27.4	12.2

Table A2. Two-way table of sub-group means and results of two-way analysis of variance for population levels (as propagules per gram of soil transformed by $Y' = \sqrt{Y + 3/8}$) of *Fusarium* spp. in check and solar treatment plots in August 1983 and May 1984.

Means 1/			Source of variation	df	MS	F
Treatment	Date: Aug. 1983	Date: May 1984	Treatment	1	971.19	13.46***
			Date	1	233.82	3.24 ns
Check	19.8	10.0	Interaction	1	351.32	4.87 *
Solar	5.4	6.4	Within subgroups	44	72.17	

1/ Propagules per gram of soil transformed by $Y' = \sqrt{Y + 3/8}$
ns = not significant; * significant at P<0.05; *** significant at P<0.001

In Table A3, the early date is May, 1984, while the later date is June, 1984, four weeks later. This analysis indicates that the population levels of *Fusarium* spp. were similar in check and solar plots and that population levels were different (greater) in June compared to May.

Table A3. Two-way table of sub-group means and results of two-way analysis of variance for population levels of *Fusarium* spp. in check and solar treatment plots in May and June 1984.

Means 1/			Source of variation	df	MS	F
Treatment	Date: May 1984	Date: June 1984	Treatment	1	273.09	3.81 ns
			Date	1	304.53	4.25 *
Check	10.0	16.2	Interaction	1	16.85	0.24 ns
Solar	6.4	10.2	Within subgroups	44		

1/ Propagules per gram of soil transformed by $Y' = \sqrt{Y + 3/8}$
ns = not significant; * significant at P<0.05

Table A4 presents results of single classification analysis of variance comparing population levels of *Fusarium* spp. between check, solar, and fumigated plots, in June 1984, when lodgepole pine seedlings were about four weeks old. The analysis indicates a significant difference between the three treatments. Orthogonal comparisons showed no significant difference between check and solar treatments, nor between solar and fumigation treatments.

Table A4. Means and analysis of variance for population levels of *Fusarium* spp. in June 1984, between check, solar, and fumigated treatments.

Treatment	Means 1/	Source of Variation	df	MS	F
Check	16.2	Treatment Effects	2	292.45	4.67 *
Solar	10.2	Within Groups	33	62.74	
Fumigated	6.4				

1/ Propagules per gram of soil transformed by $Y' = \sqrt{Y + 3/8}$
* significant at $P<0.05$

Tree Seedling Survival

Table A5 presents the average number of surviving lodgepole pine seedlings (per ft^2) in 5 subplots per plot, by treatment plot at three times during the 1984 season. Treatment plots are three solar-heated, three check, and three fumigated. The three counting times given are May 25 (2 weeks after seeding), July 3 (7 weeks), and October 1, 1984 (end of growing season). The initial variability (May 25) was due partially to differential pre-emergence damping-off and partially to irregular seeding densities.

Table A5. Average surviving seedlings per ft^2 in 5 subplots by treatment plot at 2 weeks after seeding (May 25), 7 weeks after seeding (July 3), and at the end of the growing season (October 1, 1984).

Treatment	May 25	July 3	October 1	Final Average
Solar 1	10.3	7.5	5.9	
2	23.6	18.3	17.1	12.4
3	19.5	17.0	14.1	
Check 1	26.1	23.2	18.6	
2	16.8	13.4	10.3	14.3
3	16.1	17.0	14.1	
Fumigated 1	31.1	23.5	19.1	
2	31.4	26.5	26.2	21.3
3	19.0	18.9	18.5	